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A dual active bridge dc-dc converter comprising current balancing

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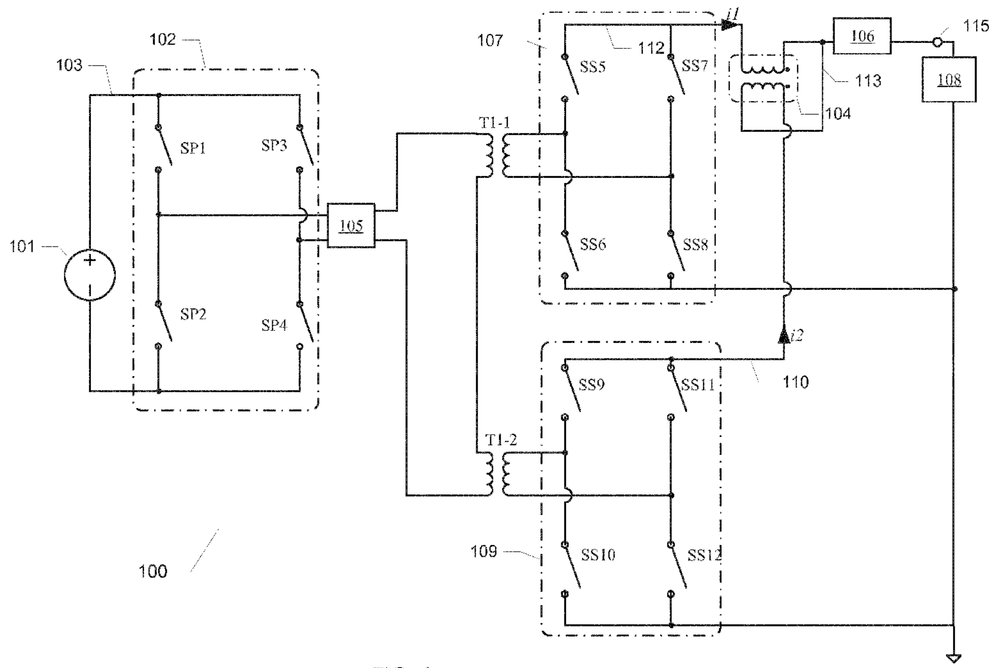

FIG. 1

(57) Abstract: The present invention relates to a dual active bridge DC-DC converter comprising a first set of n transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores where said input windings are connected in series and a first resonant network connected in series with the series connected input windings or a set of first resonant networks connected in series with respective ones of the output windings. The dual active bridge DC-DC converter further comprises a first set of rectification circuits connected to respective ones of the output windings of the first set of n transformers to supply a first set of rectified transformer voltages to a first set of rectification nodes and a current balancing transformer comprising n transformer windings connected between respective ones of the first set of rectification nodes and a common DC output voltage node to force current balancing between individual windings of the first set of output windings, where n is a positive

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integer number larger than or equal to 2.

A DUAL ACTIVE BRIDGE DC-DC CONVERTER COMPRISING CURRENT BALANCING

The present invention relates to a dual active bridge DC-DC converter comprising a first set of n transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores where said input windings are connected in series and a first resonant network connected in series with the series connected input windings or a set of first resonant networks connected in series with respective ones of the output windings. The dual active bridge DC-DC converter further comprises a first set of rectification circuits connected to respective ones of the output windings of the first set of n transformers to supply a first set of rectified transformer voltages to a first set of rectification nodes and a current balancing transformer comprising *n* transformer windings connected between respective ones of the first set of rectification nodes and a common DC output voltage node to force current balancing between individual windings of the first set of output windings, where *n* is a positive integer number larger than or equal to 2.

BACKGROUND OF THE INVENTION

Dual active bridge DC-DC converters for high power conversion where a high voltage gain is required are known in the art. The dual active bridge DC-DC converters are typically using one or several of the following design principles to cope with high input voltages and large secondary side currents:

1. The use of high power rated converter components such as high current rated switching devices, capacitors, inductors, transformers etc.;
2. Multiple interleaved DC-DC converters;
3. Multiple parallelly connected DC-DC converters.

Dual active bridge (DAB) DC-DC converters in accordance with point 1 are the most common solution, but results in major design challenges because the components of the DAB DC-DC converter, in particular high current rated switching devices, operate in a very harsh environment and experiences a high thermal stress. This high thermal stress is a substantial disadvantage because it increases the risk of thermal breakdown and hence reduces overall reliability of the DAB DC-DC converter.

Dual active bridge (DAB) DC-DC converters in accordance with point 2 can be realized in poly-phase system, i.e. three or more phases, have found increased attention in recent years because interleaving with phase shifted control signals can lower the current stress on active and passive components. However, the unbalanced current sharing on between multiple parallelly coupled secondary side circuits of the converter is a major problem. The only known remedy is the use of an extensive current monitoring system in each secondary circuit of the DAB DC-DC converter. However, this remedy increases the converter complexity from a system point of view, cost point of view and control point of view.

DAB DC-DC converters in accordance with point 3, where several DC-DC converters are connected in parallel on both the primary side and secondary side, share numerous disadvantages with those under point 2. DAB DC-DC converters according to this configuration typically achieves a high voltage gain by using a transformer with a high tums ratio. This leads to major design challenges of the efficiency of the transformer.

Therefore, it would be desirable to provide DAB DC-DC converters which eliminate at least some of these limitations or drawbacks of prior art DAB DC-DC converters. Novel DAB DC-DC converter topologies and circuits possessing high voltage gain and high power capability without suffering from the above disadvantages are desirable. Novel DAB DC-DC converter topologies and circuits comprising multiple parallelly coupled secondary side circuits without unbalanced current sharing problems are desirable. Likewise, novel DAB DC-DC converter topologies with reduced design complexity, reduced costs and improvised conversion efficiency are desirable.

SUMMARY OF THE INVENTION

A first aspect of the invention relates to a dual active bridge DC-DC converter comprising: a converter input for receipt of a DC input voltage,

- a first set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,
- a first input driver for generating a first pulse width modulated drive signal at a first

phase angle and applying the first pulse width modulated drive signal to the series connected input windings of the first set of *n* transformers;

- a first set of *n* rectification circuits connected to respective ones of the output windings of the first set of *n* transformers to supply a first set of *n* rectified transformer voltages to a first set of *n* rectification nodes,
- a first resonant network connected in series with the series connected input windings or a first set of *n* resonant networks connected in series with respective ones of the output windings,
- a current balancing transformer comprising *n* transformer windings connected between respective ones of the first set of *n* rectification nodes and a common DC output voltage node to force current balancing between individual windings of the first set of output windings;

n being a positive integer number larger than or equal to 2.

The *n* transformer windings of the current balancing transformer are preferably wound around a common magnetically permeable core to provide strong magnetic coupling between the *n* transformer windings. The *n* transformer windings of the current balancing transformer are preferably wound around a shared leg structure of the common magnetically permeable core to conduct equal amounts of magnetic flux through each transformer winding. Alternatively, the *n* transformer windings of the current balancing transformer may be implemented as *n* magnetically coupled inductors.

The first input driver may comprise well-known driver topologies such as a half-bridge driver or an H-bridge driver configured for applying the first pulse width modulated drive signal across the series connected input windings of the first set of n transformers. According to one such embodiment the first input driver comprises an H-bridge having a pair of complementary outputs connected to respective winding terminations of the first and second input windings. The first input driver may comprise a single semiconductor switch or a plurality of appropriately arranged semiconductor switches such as IGBT switches or MOSFET switches to form well-known driver topologies.

The skilled person will understand that each rectification circuit of the first set of rectification circuits may comprise an active rectification circuit or passive rectification circuit. Each of the active rectification circuits may comprise a plurality of controllable transistor switches, e.g. MOSFETs while each of the passive rectification circuits may comprise a plurality of semiconductor diodes for example four semiconductor diodes configured as a full-wave rectifier as discussed in additional detail below with reference to the appended drawings.

The individual transformers of the first set of *n* transformers are preferably nominally identical to facilitate equal voltage division between the input windings of individual transformers and facilitate equal current sharing between the output windings of the *n* transformers and other secondary side circuitry like the *n* rectification circuits. The first set of *n* transformers may comprise between 2 and 6 individual transformers.

The skilled person will appreciate that the current balancing transformer provides numerous benefits to DAB DC-DC converter topology comprising a *n* parallelly coupled secondary side circuits. These benefits include elimination, or at least a significant reduction, of output current mismatches caused by practically occurring mismatches between electrical components and/or drive voltage waveform mismatches between the primary side circuits and secondary side circuits. The elimination of the output current mismatches allows parallel connection of numerous secondary side circuits and serial connection of numerous input side circuits without inducing significant current imbalances between the individual secondary side circuits. Furthermore, each secondary side circuit and each primary side circuit can be rated at a much lower power rating compared to a single high-power secondary or primary side circuit. Hence, enabling utilization of relatively low cost active and passive components, such as MOSSFET and IGBT transistors, and also reduced thermal stress. The reduced thermal stress helps to markedly increase the life time expectancy of present DAB DC-DC converters.

Certain embodiments of the present dual active bridge DC-DC converters are polyphase DAB DC-DC converters where the term poly-phase designates three or more separate input signal phases. These poly-phase dual active bridge DC-DC converter embodiments comprises, in addition to the first set of *n* transformers and its associated primary side circuitry and secondary circuitry as discussed above a second set of *n* transformers and a third set of *n* transformers. Each transformer of the second and third sets of *n* transformers comprises respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores (not shown). Hence, these embodiments of the dual active bridge DC-DC converter further comprise:

- a second set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,
- a second input driver for generating a second pulse width modulated drive signal at a second phase angle shifted at a first predetermined phase relative to the first phase angle, and applying the second pulse width modulated drive signal to the series connected input windings of the second set of *n* transformers,
- a second resonant network connected in series with the series connected input windings of the second set of n transformers or a second set of *n* resonant networks connected in series with respective ones of the output windings of the second set of *n* transformers; and
- a third set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series;
- a third input driver for generating a third pulse width modulated drive signal at a third phase angle shifted at a second predetermined phase relative to the first phase angle, and applying the second pulse width modulated drive signal to the series connected input windings of the third set of n transformers,
- a third resonant network connected in series with the series connected input windings of the third set of *n* transformers or a set of third resonant networks connected in series with respective ones of the output windings of the third set of *n* transformers; and
- a second set of *n* rectification circuits connected to respective ones of the output windings of the second set of *n* transformers and configured for supplying a second set of rectified transformer voltages to respective ones of the first set of *n* rectification nodes,
- a third set of *n* rectification circuits connected to respective ones of the output windings of the third set of *n* transformers and configured for supplying a third set of

n rectified transformer voltages to respective ones of the first set of *n* rectification nodes.

The skilled person will appreciate that the first, second and third sets of *n* rectification circuits may be viewed a single set of *n* three-phase rectification circuits.
In this embodiment, the first predetermined phase may be 120 degrees and the second predetermined phase may be 240 degrees such that the first, second and third pulse width modulated drive signals are placed at 0 degrees, 120 degrees and 240 degrees.

Another poly-phase DAB DC-DC converter embodiment comprises at least four separate phases such that the dual active bridge DC-DC converter further comprises at least:
- a fourth set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,
- a fourth input driver for generating a fourth pulse width modulated drive signal at a fourth phase angle shifted with a third predetermined phase relative to the first phase angle, and applying the fourth pulse width modulated drive signal to the series connected input windings of the fourth set of n transformers,
- a fourth resonant network connected in series with the series connected input windings of the fourth set of *n* transformers or a fourth set of *n* resonant networks connected in series with respective ones of the output windings of the fourth set of *n* transformers,
- a fourth set of *n* rectification circuits connected to respective ones of the output windings of the fourth set of *n* transformers and configured for supplying a fourth set of rectified transformer voltages to respective ones of the first set of *n* rectification nodes.

In the latter embodiment, the first predetermined phase may be 90 degrees, the second predetermined phase 180 degrees and the third predetermined phase 270 degrees. The skilled person will understand that the predetermined phases may be distributed in a correspondingly regular manner around 360 degrees in poly-phase DAB DC-DC converters comprising more than four phases.

One embodiment of the first input driver comprises a first controllable semiconductor switch connected between the converter input and a driver output and a second controllable semiconductor switch connected between the driver output and a negative DC supply rail such as ground; said driver output being connected to the series connected input windings of the first set of *n* transformers. The first and second control terminals of the first and second controllable semiconductor switches, respectively, may be connected to a modulated drive signal source. Each of the first and second controllable semiconductor switches of the first input driver may comprise a MOSFET or an IGBT.

Each rectification circuit of the first set of *n* rectification circuits may comprise an active rectification circuit or a passive rectification circuit. The active rectification circuit comprises a plurality of controllable semiconductor switches such that respective switching time instants of the switches can be controlled via respective control terminals of the semiconductor switches by an appropriately timed control signal as discussed in additional detail below with reference to the appended drawings. The passive rectification circuit may comprise a plurality of semiconductor diodes connected to form a full-wave rectifier.

As outlined above, the output windings of the first set of *n* transformers to respective one of *n* individual single-phase rectification circuits or *n* individual poly-phase rectification circuits. According to a preferred embodiment the respective number of turns of the *n* transformer windings of the current balancing transformer are selected such that:
where *n* is even such as two, four or six; each of the *n* transformer windings has the same number of turns, N;
where *n* is odd such as 3, 5 and 7; the current balancing transformer comprises *(n-1)* transformer windings with the same number of turns, N, and at least one transformer winding with (n-1)*N turns.

Hence, if *n* is equal to three, the current balancing transformer comprises three transformer windings amongst which two windings each has N turns and another transformer winding has 2*N turns.

A second aspect of the invention relates to a method of adjusting load power supplied to a converter load by a dual active bridge DC-DC converter according to any of the above-described embodiments thereof. The method comprising:
- applying a first pulse width modulated drive signal at a first phase angle to the series connected input windings of the first set of n transformers,
- applying a second pulse width modulated drive signal at a second phase angle to respective control terminals of a plurality of controllable semiconductor switches of each rectification circuit of the first set of *n* rectification circuits,
- adaptively adjusting a phase difference between the first phase angle and the second phase angle to reach a desired DC output voltage of the dual active bridge DC-DC converter. A duty cycle of the first pulse width modulated drive signal may lie between 10 % and 90 % e.g. about 50 % and a duty cycle of the second pulse width modulated drive signal may lie between 10 % and 90 % e.g. about 50 %. Hence, the duty cycles of the first and second pulse width modulated drive signals may be equal.

The phase difference between the first and second pulse width modulated drive signals may be used to control load power to a load connected to the DC output voltage of the converter as discussed in additional detail below with reference to the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the invention will be described in more detail in connection with the appended drawings, in which:

FIG. 1 is a schematic diagram of a dual active bridge DC-DC converter in accordance with a first embodiment of the invention,

FIG. 2 is a schematic diagram of a dual active bridge DC-DC converter in accordance with a second embodiment of the invention,

FIG. 3 is a schematic diagram of a poly-phase dual active bridge DC-DC converter in accordance with a third embodiment of the invention,

FIG. 4 shows schematic diagram of a dual active bridge DC-DC converter in accordance with a fourth embodiment of the invention,

FIG. 5 shows schematic diagram of a poly-phase dual active bridge DC-DC converter in accordance with a fifth embodiment of the invention

FIG. 6 is a circuit diagram of various exemplary embodiments of resonant networks for use in the present dual active bridge DC-DC converters,

FIG. 7A) is a schematic drawing of a first exemplary current balancing transformer of the present dual active bridge DC-DC converters; and

FIG. 7B) is a schematic drawing of a second exemplary current balancing transformer of the present dual active bridge DC-DC converters.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In the following, various exemplary embodiments of the present dual active bridge DC-DC converters are described with reference to the appended drawings. The skilled person will understand that the accompanying drawings are schematic and simplified for clarity and therefore merely show details which are essential to the understanding of the invention, while other details have been left out. Like reference numerals refer to like elements or components throughout. Like elements or components will therefore not necessarily be described in detail with respect to each figure. It will further be appreciated that certain actions and/or steps may be described or depicted in a particular order of occurrence while those skilled in the art will understand that such specificity with respect to sequence is not actually required.

FIG. 1 shows a schematic electrical diagram of a dual active bridge (DAB) DC-DC converter 100 in accordance with a first embodiment of the invention. The DAB DC-DC converter 100 may be viewed as a single-phase embodiment of the present DAB DC-DC converter topologies. The DAB DC-DC converter 100 comprises a converter input 103 for receipt of a DC input voltage produced by a DC input voltage or energy source 101. The skilled person will understand that the DC input voltage source 101 may comprise a rectified mains voltage for example delivered from a rectification and smoothing circuit connected to a single phase or three-phase mains voltage. Hence, the DC input voltage may be between 380 V and 565 V in grid connected systems. The DAB DC-DC converter 100 comprises an H-bridge input driver 102 comprising four controllable semiconductor switches SP1, SP2, SP3 and SP4 generating a first pulse width modulated drive signal (not shown) at a first phase angle. The skilled person will understand that the first pulse width modulated drive signal may be generated by supplying appropriate drive signal to respective control terminals (not shown) of the four controllable semiconductor switches SP1, SP2, SP3 and SP4 of the H-bridge input driver. Each of the four controllable semiconductor switches SP1, SP2, SP3 and SP4 may for example comprise a MOSFET or an IGBT with a gate terminal. The latter terminals are utilised to control state switching of the MOSFET or an IGBT devices between a conducting state (on-state) and a non-conducting state (off-state). The DAB DC-DC converter 100 comprises a set of transformers comprising first and second transformers T1-1 and T1-2 in the present embodiment but may comprise one or more additional transformers in other embodiments as discussed in further detail below. Each of the first and second transformers T1-1 and T1-2 comprises an input/primary winding and output/secondary winding magnetically coupled to each other through respective magnetically permeable core e.g. an E-core or toroidal core. The winding ratio of each of the first and second transformers T1-1 and T1-2 may vary depending on factors like the DC input voltage, number of transformers and a desired DC output voltage of the converter 100. In some embodiments, a winding ratio between 4 and 20 such as about 9 has proven useful. The first and second transformers T1-1 and T1-2 are preferably nominally identical to facilitate equal voltage division between the input windings of first and second transformers and facilitate equal current sharing between the output windings and other secondary side circuitry.

The first pulse width modulated drive signal generated by the H-bridge input driver is applied to the series connected input windings of first and second transformers T1-1 and T1-2 either through a resonant network 105, as illustrated in the present embodiment, or directly (without intermediate electric components like inductors and capacitors, to the series connected input windings. In the latter embodiment, the resonant network 105 is moved from the primary side to the secondary side of the converter 100, more specifically to each of the output windings of the first and second transformers T1-1 and T1-2 on the secondary side of the DAB DC-DC converter. In the latter case, appropriately modified first and second resonant networks (not shown) are connected in series with respective ones of the output windings of the first and second transformers T1-1 and T1-2 by taken into account the impedance transformation caused by the winding ratios of the first and second transformers T1-1 and T1-2 and the number of parallelly connected output windings. Three exemplary embodiments of the resonant network 105 are schematically illustrated on FIG. 6. The resonant network 105 may comprise a single series connected inductor L_{AC}

connected in series with the series connected input windings of first and second transformers T1-1 and T1-2 or a series connected combination of an inductor L_{AC} and capacitor C_{AC}. The resonant network 105 may alternative comprise a pair of series connected inductors L_{AC1}, L_{AC2} and with a midpoint between these connected to a first terminal of a capacitor C_{AC} where the series connected inductors are inserted in series with input windings of the first and second transformers T1-1 and T1-2 and the other end of C_{AC} is connected to an ac ground potential.

The duty cycle of the first pulse width modulated drive signal may be 50 % and the first phase angle is an arbitrary value which is used to define respective phase shifts to additional pulse width modulated drive signal(s) and certain pulse width modulated rectification signals as discussed in additional detail below. The first pulse width modulated drive signal may have a frequency between 1 kHz and 1 MHz depending on numerous performance requirements of a specific design of the present DAB DC-DC converter 100 such as a desired maximum power output, properties of the first and second transformers and properties of the resonant network 105 or networks.

The DAB DC-DC converter 100 additionally comprises a set of rectification circuits comprising first and second active rectification circuits 107, 109 in the present embodiment but may comprise one or more additional active rectification circuits in other embodiments as discussed in further detail below. The first and second active rectification circuits 107,109 are connected to respective ones of the output windings of the first and second transformers T1-1 and T1-2 to supply respective rectified transformer voltages to first and second rectification nodes 112, 110 of the converter. Each of the first and second active rectification circuits comprises a full-wave rectifier in the present embodiment. The first active rectification circuit 107 comprises four controllable semiconductor switches, i.e. SS5, SS6, SS7 and SS8, connected to respective ends of the first output winding for receipt of the ac voltage induced in the first output winding. The second active rectification circuit 109 likewise comprises four controllable semiconductor switches, i.e. SS9, SS10, SS11 and SS12, connected to respective ends of the second output winding (of transformer T1-2) for receipt of the ac voltage induced in the second output winding. Each of the controllable semiconductor switches SS5, SS6, SS7, SS8, SS9, SS10, SS11 and SS12 of these rectification circuits may for example comprise a MOSFET or an IGBT with a gate terminal. The latter terminals are utilised to control state switching of the MOSFET or an IGBT devices between a conducting state (on-state) and a non-conducting state (off-state).

Hence, the term “active” in “active rectification circuit” means that the latter is based on controllable semiconductor switches, e.g. transistors, where the switching time instant can be controlled via the respective control terminals of the switches by an appropriately timed control signal as opposed to a passive rectification circuit based on diodes. The latter control signal may in particular comprise a second pulse width modulated drive signal (not shown) that is off-set with a fixed or adjustable phase angle relative to the first pulse width modulated drive signal driving the input windings. The phase difference between the first and second pulse width modulated drive signals may be used to control load power to a load 108 connected to a DC out terminal or node 115 of the converter 100. Hence, this method of adjusting the load power supplied to the converter load by the DC-DC converter 100 preferably comprising:

- applying the first pulse width modulated drive signal at a first phase angle to the series connected input windings of the first set of transformers,
- applying the second pulse width modulated drive signal at a second phase angle to respective control terminals of a plurality of controllable semiconductor switches of each rectifier of the first set of rectifiers,
- adaptively adjusting a phase difference between the first phase angle and the second phase angle to reach a desired DC output voltage of the dual active bridge DC-DC converter. The skilled person will understand that the adaptive adjustment of the phase difference may be carried out by a suitable feedback voltage regulation loop sensing the instantaneous DC output voltage and comparing the latter with a certain DC reference/set-point voltage indicating a desired DC output voltage of the DC-DC converter 100.

The DAB DC-DC converter 100 additionally comprises a current balancing transformer 104 which comprises first and second transformer windings wound around a common magnetically permeable core (not shown). The number of turns of the first transformer winding is preferably identical to the number of turns of the second transformer winding in the present embodiment which comprises an even number of parallel secondary side circuits, i.e. two as discussed below in additional detail. One end of each of the first and second transformer windings are coupled together to form common DC output voltage node 113 while the opposite ends of the first and second transformer windings are connected to respective ones of the first and second rectification nodes 112, 110. Hence, each transformer winding is connected between a rectification nodes and the common DC output voltage node 113 and thereby forces current balancing between the output windings of the first and second transformers T1-1 and T1-2. The current balancing effect on currents flowing through first and second active rectification circuits 107,109 and their associated output winding can be understood by noting the transformer exhibits a high impedance against differential components of the first and second output currents i1 and i2 and a low impedance in respect of common mode current components of the first and second output currents i1 and i2. Construction details of the current balancing transformer 104 are discussed in detail below with reference to FIG. 7A) for the case of an even number of parallel rectification circuits. The DAB DC-DC converter 100 comprises an optional lowpass or smoothing filter 106 connected between the common DC output voltage node 113 and an externally accessible converter output node or terminal 115 delivering the output DC voltage and current to the load. The lowpass or smoothing filter 106 may be utilized to attenuate unwanted harmonic components of the rectified mains voltage. The load 108 is connectable to the converter output node or terminal 115.

The skilled person will appreciate that the current balancing transformer 104 provides numerous benefits to DAB DC-DC converter topologies comprising a plurality of parallelly coupled secondary side circuits. These benefits include the elimination, or at least a significant reduction, of output current mismatches, such as i1 and i2 discussed above, caused by practically occurring mismatches between electrical components and/or drive voltage waveform mismatches between the primary side circuits and secondary side circuits. The elimination of the output current mismatches allows numerous secondary side circuits to be coupled in parallel and numerous input side circuits coupled in series as illustrated above, without inducing significant current imbalances between the individual secondary side circuits. Furthermore, each secondary side circuit and each primary side circuit can be rated at a much lower power rating compared to a single high-power secondary or primary side circuit and hence enabling utilization of relatively low cost active and passive components, such as MOSSFET and IGBT transistors, and also reduced thermal stress. The reduced thermal stress helps to markedly increase the life time expectancy of present DAB DC-DC converters.

The skilled person will appreciate that the series connection of the respective input windings of the set of transformers, e.g. the first and second transformers T1-1 and T1-2, provides numerous benefits to DAB DC-DC converter topologies comprising a plurality of series connected primary side circuits to achieve a high voltage gain in a grid-connected power converter. The transformer for each of the stages can be realized with a lower turns ratio for the input and output windings thereby significantly easing the transformer design process and enabling a modular design approach of simplified transformers.

FIG. 2 shows a schematic electrical diagram of a dual active bridge (DAB) DC-DC converter 200 in accordance with a second embodiment of the invention. The DAB DC-DC converter 200 may be viewed as another single-phase embodiment of the present DAB DC-DC converter topologies. The DAB DC-DC converter 200 has similar components and topology to the first embodiment discussed above except for being extended/expanded with an additional transformer T1-3 and its associated primary side circuitry and secondary circuitry. Hence, the DAB DC-DC converter 200 comprises a set of transformers comprising first, second and third individual transformers T1-1, T1-2 and T1-3 while alternative embodiments may comprise one or more additional transformers with associated primary side circuitry and secondary circuitry. The DAB DC-DC converter 200 additionally comprises an H-bridge input driver 202 which may be largely identical to the previously discussed H-bridge 102 albeit now supplying the first pulse width modulated drive signal to the three series connected input windings of the first, second and third transformers T1-1, T1-2 and T1-3. The secondary circuitry of the DAB DC-DC converter 200 likewise includes a third active rectification circuit 211, connected in parallel to the first and second active rectification circuit 207, 209. The third active rectification circuit 211 comprises four controllable semiconductor switches, i.e. SS13, SS15, SS14 and SS16, connected to respective ends of the third output winding for receipt of the ac voltage induced in the third output winding in response to drive voltage across the third input winding of T1-3. The skilled person will notice that the dual active bridge (DAB) DC-DC converter 200 also comprises an expanded current balancing transformer 204 reflecting the use of three parallel active rectification circuits 207, 209 and 211. The current balancing transformer 204 comprises first, second and third transformer windings wound around a common magnetically permeable core (not shown). One end of each of the first, second and third transformer windings are coupled together to form common DC output voltage node 213 while the opposite ends of the first and second transformer windings are connected to respective ones of the first and second rectification voltage nodes. The respective output currents i1, i2 and i3 of the three parallelly connected active rectification circuits 207, 209 and 211 are illustrated on the drawing. Construction details of the transformer of the current balancing transformer 204 are discussed in detail below with reference to FIG. 7B) for the case of an odd number of parallel rectification circuits.

FIG. 3 is a schematic diagram of a poly-phase DAB DC-DC converter 300 in accordance with a third embodiment of the invention where the term poly-phase designates three separate input signal phases. The poly-phase dual active bridge DC-DC converter 300 comprises, in addition to a first set of transformers, T1-1 and T1-2 and its associated primary side circuitry and secondary circuitry as discussed above in connection with the first DC-DC converter embodiment 100, a second set of transformers T2-1, T2-2 and a third set of transformers T3-1, T3-2. Each transformer of the second and third sets of transformers comprises respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores (not shown). The input windings of the second set of transformers T2-1, T2-2 are connected in series and the input windings of the third set of transformers T3-1, T3-2 are connected in series. The respective sets of series connected input windings of the first, second and third sets of transformers are connected to a common start-point or neutral node 317. The poly-phase DAB DC-DC converter 300 further comprise a second input driver 302b for generating a second pulse width modulated drive signal (not shown) at a second phase which is shifted with a first predetermined phase angle relative to the first phase angle. The skilled person will appreciate that considering the three phase nature of the present embodiment the second phase may be shifted 120 degrees relative to the first phase angle of the first pulse width modulated drive signal generated by the first input driver 302a. The second pulse width modulated drive signal is applied to the series connected input windings of the second set of transformers T2-1, T2-2. The resonant network assembly 305 comprises three separate resonant networks connected at one end to respective ones of first, second and third input drivers 302a, 302b, 302c. The second resonant network (not shown) of the resonant network assembly 305 is connected in series with the series connected input windings of the second set of transformers T2-1 and T2-2. Alternatively, the second resonant network may be connected in series with each of the output windings of the first and second transformers T2-1 and T2-2 of the second set on the secondary side of the poly-phase DAB DC-DC converter 300 in a corresponding manner as the one discussed above. In either case, one end of the first output winding of the transformer T2-1 is connected to a second active rectification circuit comprising the two controllable semiconductor switches, i.e. SS9 and SS8, while the other end of the first output winding of the transformer T2-1 is connected to two further pairs of controllable semiconductor switches through the respective output windings of transformers T1-1, T3-1. The skilled person will appreciate that the three separate pairs of controllable semiconductor switches SS7, SS8; SS9, SS10 and SS11, SS12 form three parallelly connected active rectification circuits, or a three-phase active rectifier, configured to supply three rectified and mutually phase-shifted transformer voltages to the first rectification node 312 of the converter 300. The third input driver 302c is configured to generate a third pulse width modulated drive signal (not shown) at a third phase which is shifted with a second predetermined phase angle relative to the first phase angle. The skilled person will appreciate that considering the three-phase nature of the present embodiment the third phase may be shifted 240 degrees relative to the first phase angle of the first pulse width modulated drive signal generated by the first input driver 302a. The third pulse width modulated drive signal is applied to the series connected input windings of the third set of transformers T3-1, T3-2. A third resonant network (not shown) of the resonant network assembly 305 is connected in series with the series coupled input windings of the third set of transformers or connected in series with each of the output windings of the first and second transformers T3-1 and T3-2 of the third set of transformers on the secondary side of the poly-phase DAB DC-DC converter 300 in a corresponding manner to the one discussed above. Three separate pairs of controllable semiconductor switches

SS13, SS14; SS15, SS16 and SS17, SS18 form three parallelly connected active rectification circuits, or a second three-phase active rectifier of the converter 300, configured to supply three rectified and mutually phase-shifted transformer voltages to the second rectification node 310 of the converter 300.

The poly-phase DAB DC-DC converter 300 additionally comprises a current balancing transformer 304 comprising first and second transformer windings wound around a common magnetically permeable core (not shown). One end of each of the first and second transformer windings are coupled together to form common DC output voltage node 313 while the opposite ends of the first and second transformer windings are connected to respective ones of the first and second rectification nodes 312, 310. Hence, each transformer winding is connected between a rectification nodes and the common DC output voltage node 313 and thereby forces current balancing between the respective sets of output windings of the transformers of the first and second sets transformers. The respective output currents i1 and i2 of the two parallelly connected three-phase active rectification circuits are illustrated on the drawing. Construction details of the transformer of the current balancing transformer 304 are discussed in detail below with reference to FIG. 7A) and FIG. 7B).

FIG. 4 shows a schematic electrical diagram of a DAB DC-DC converter 400 in accordance with a fourth embodiment of the invention. The DAB DC-DC converter 400 may be viewed as passive rectification circuit embodiment of the single-phase embodiment of the DAB DC-DC converter 100 discussed above. The DAB DC-DC converter 400 comprises first and second passive full-wave rectification circuits 407,409 are connected to respective ones of output windings of first and second transformers T1-1 and T1-2 to supply respective rectified transformer voltages to first and second rectification nodes 412, 410 of the converter. The first passive full-wave rectification circuit 407 comprises four semiconductor diodes, i.e. D1, D2, D3 and D4 connected to respective ends of the first output winding of T1-1 for receipt of the ac voltage induced in the first output winding. The second passive rectification circuit 409 likewise comprises four semiconductor diodes, i.e. D5, D6, D7 and D8, connected to respective ends of the second output winding of transformer T1-2 for receipt of the ac voltage induced in the second output winding in response to ac voltage and current through the second input winding. The skilled person will appreciate that the present DAB DC-DC converter 400 is merely capable of supporting unidirectional power flow from the DC input voltage or energy source 401 to the converter load 408. This property is different from the above-discussed DAB DC-DC converter topologies 100, 200, 300 which by virtue of their active rectification circuits are capable of supporting bi-directional power/energy flow by shifting the relative phase between the one or more pulse width modulated drive signals and the corresponding rectification control signals. In particular, a power flow in the opposite/reverse direction from the load 408 to the DC input voltage or energy source 401 (negative power flow) can be achieved by setting a negative relative phase angle between the pulse width modulated drive signal(s) at the primary side circuitry and the corresponding rectification control signals on the secondary side circuitry.

FIG. 5 is a schematic diagram of another poly-phase DAB DC-DC converter 300 in accordance with a fifth embodiment of the invention. The poly-phase dual active bridge DC-DC converter 500 comprises four phases with associated sets of transformers T1-1, T1-2; T2-1, T2-2; T3-1, T3-2 and T4-1, T4-2. Each transformer of the first, second, third and fourth sets of transformers comprise respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores (not shown). The input windings of each set of transformers of the first, second, third and fourth sets of transformers are connected in series as discussed before. The poly-phase DAB DC-DC converter 500 furthermore comprises: a first input driver 502a for generating a first pulse width modulated drive signal (not shown) at a first predetermined phase angle, e.g. reference phase, a second input driver 502b for generating a second pulse width modulated drive signal (not shown) at a second phase which is shifted with a first predetermined phase angle relative to the first phase angle, a third input driver 502c for generating a third pulse width modulated drive signal (not shown) at a third phase which is shifted with a second predetermined phase angle relative to the first phase angle and fourth input driver 502d for generating a fourth pulse width modulated drive signal (not shown) at a fourth phase which is shifted with a third predetermined phase angle relative to the first phase angle. The skilled person will appreciate that considering the four phase nature of the present embodiment the second phase may be shifted 90 degrees relative to the first predetermined phase angle of the first pulse width modulated drive signal, the third phase may be shifted 180 degrees relative to the first predetermined phase angle and the fourth phase may be shifted 270 degrees relative to the first predetermined phase angle. A resonant network assembly 505 comprises four preferably identical resonant networks connected in series with the series connected input windings of the respective sets of transformers T1-1, T1-2; T2-1, T2-2; T3-1, T3-2 and T4-1, T4-2. A first four-phase active rectification circuit comprising controllable semiconductor switches SS9 - SS14 is configured to generate four rectified and mutually phase-shifted transformer voltages to the first rectification node 512 of the converter 500. A second four-phase active rectification circuit comprising controllable semiconductor switches SS15 – SS22 is configured to generate four additional rectified and mutually phase-shifted transformer voltages to the second rectification node 510 of the converter 500. The poly-phase DAB DC-DC converter 500 additionally comprises a current balancing transformer 504 comprising a transformer with first and second transformer windings wound around a common magnetically permeable core (not shown). One end of each of the first and second transformer windings are coupled together to form common DC output voltage node 513 while the opposite ends of the first and second transformer windings are connected to respective ones of the first and second rectification nodes 512, 510. The number of turns of the first and second transformer windings is preferably identical in the present embodiment which comprises an even number of, i.e. two, parallel rectification circuits. Construction details of the transformer of the current balancing transformer 104 are discussed in detail below with reference to FIG. 7A) for the case of an even number of parallel rectification circuits.

FIG. 7A) is a schematic drawing of a first exemplary current balancing transformer 104, 304, 504 for use in either of the previously discussed DAB DC-DC converter embodiments 100, 300, 500 comprising an even number of transformer sets, e.g. T1-2 and T1-2 or T2-1 and T2-2 etc. The first exemplary current balancing transformer 104, 304, 504 comprises an even number of transformer windings 752, 754, 756, 75n. Hence, the first current balancing transformer 104, 304, 504 is suitable for use in DAB DC-DC converter embodiments generally comprising *n* parallelly coupled rectification circuits, e.g. single phase rectifiers or three-phase rectifiers etc., where n is a positive even integer number for example 2, 4 or 6. The first current balancing transformer 104, 304, 504 comprises a magnetically permeable core 755 with E-shaped geometry or outline. A pair of air openings or windows 760 formed in the core material provides a substantially straight centre leg 762 arranged in-between a pair adjacent outer legs. The individual transformer windings 752, 754, 756, 75n are arranged adjacent to each other and wound around the substantially straight centre leg 762. The first transformer winding 752 has a first end 752a which may be connected to the previously discussed first rectification node i.e. 112, 312, 512 and the second transformer winding 754 has a first end 754a which may be connected to the previously discussed second rectification node i.e. 110, 310, 510. The opposite ends or terminations of the first and second transformer windings (and all further transformer windings as the case may be) are electrically coupled together to form a common node or wire 713 for connection to the respective DC output nodes 113, 313, 513 discussed previously. The transformer windings 752, 754, 756, 75_n preferably possess the same number of turns N. N may in practice be a number between 6 and 20 and possibly depend on core dimensions. The skilled person will appreciate that other embodiments of the magnetically permeable core 755 may possess various other shapes – for example a toroid shape, a rectangular shape etc.

FIG. 7B) is a schematic drawing of a second exemplary current balancing transformer 204 for use in the previously discussed DAB DC-DC converter embodiment 200 comprising an odd number of transformer sets, i.e. three transformer sets. The magnetically permeable core 775 may be largely identical to the core 755 discussed above and the individual transformer windings 772, 774, 776, 85n may likewise be arranged adjacent to each other around a substantially straight centre leg 772. The second exemplary current balancing transformer 204 comprises an odd number of transformer windings 772, 774, 776, 77n - for example three, five or seven transformer windings. Hence, the second current balancing transformer 204 is suitable for use in DAB DC-DC converter embodiments generally comprising *n* parallelly coupled rectification circuits, e.g. single phase rectifiers or three-phase rectifiers etc., where n is a positive odd integer number for example 3, 5 or 7. In addition to the odd number of transformer windings, the number of turns of one of the transformer windings 77n is different from the residual (n-1) transformer windings 772, 774, 776 which all may have the same number of turns, e.g. N as schematically indicated. The number of turns of the transformer winding 77n is preferably set to: (n-1)*N, where n represents the number of transformer sets, or correspondingly, the number of parallelly connected single-phase or poly-phase rectification circuits.

The transformer winding 77n has 2N turns in the present embodiment because of n=3. A first end 776a of the transformer winding 77n is connected to the previously discussed first rectification node 212 (please refer to FIG. 2) and the second end of the transformer winding 77n is connected to a common node or wire 783 for connection to the DC output nodes 213 discussed previously. The first end 772a of the second transformer winding 772 is connected to the previously discussed second rectification node 210 and the first end 774a of the third transformer winding 774 is connected to the previously discussed third rectification node 210a. The opposite ends or terminations of the first and second transformer windings 772, 774 (and all further transformer windings as the case may be) are electrically coupled together to the common node or wire 783. N may in practice be a number between 6 and 20.

CLAIMS

1. A dual active bridge DC-DC converter comprising:

- a converter input for receipt of a DC input voltage,
- a first set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,
- a first input driver for generating a first pulse width modulated drive signal at a first phase angle and applying the first pulse width modulated drive signal to the series connected input windings of the first set of *n* transformers;
- a first set of *n* rectification circuits connected to respective ones of the output windings of the first set of *n* transformers to supply a first set of *n* rectified transformer voltages to a first set of *n* rectification nodes,
- a first resonant network connected in series with the series connected input windings or a first set of *n* resonant networks connected in series with respective ones of the output windings,
- a current balancing transformer comprising *n* transformer windings connected between respective ones of the first set of *n* rectification nodes and a common DC output voltage node to force current balancing between individual windings of the first set of output windings;

n being a positive integer number larger than or equal to 2.

2. A dual active bridge DC-DC converter according to claim 1, wherein the first set of *n* transformers comprises between 2 and 6 individual transformers.

3. A dual active bridge DC-DC converter according to claim 1 or 2, further comprising:

- a second set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,
- a second input driver for generating a second pulse width modulated drive signal at a second phase angle shifted at a first predetermined phase relative to the first phase angle, and applying the second pulse width modulated drive signal to the series connected input windings of the second set of *n* transformers,

- a second resonant network connected in series with the series connected input windings of the second set of n transformers or a second set of *n* resonant networks connected in series with respective ones of the output windings of the second set of *n* transformers; and

- a third set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series;

- a third input driver for generating a third pulse width modulated drive signal at a third phase angle shifted at a second predetermined phase relative to the first phase angle, and applying the second pulse width modulated drive signal to the series connected input windings of the third set of n transformers,

- a third resonant network connected in series with the series connected input windings of the third set of *n* transformers or a set of third resonant networks connected in series with respective ones of the output windings of the third set of *n* transformers; and

- a second set of *n* rectification circuits connected to respective ones of the output windings of the second set of *n* transformers and configured for supplying a second set of rectified transformer voltages to respective ones of the first set of *n* rectification nodes,

- a third set of *n* rectification circuits connected to respective ones of the output windings of the third set of *n* transformers and configured for supplying a third set of *n* rectified transformer voltages to respective ones of the first set of *n* rectification nodes.

4. A dual active bridge DC-DC converter according to claim 3, wherein the first predetermined phase is 120 degrees and the second predetermined phase is 240 degrees.

5. A dual active bridge DC-DC converter according to claim 3, further comprising at least:

- a fourth set of *n* transformers comprising respective input windings and respective output windings magnetically coupled to each other through respective magnetically permeable cores; said input windings being connected in series,

- a fourth input driver for generating a fourth pulse width modulated drive signal at a fourth phase angle shifted with a third predetermined phase relative to the first phase angle, and applying the fourth pulse width modulated drive signal to the series connected input windings of the fourth set of *n* transformers,
- a fourth resonant network connected in series with the series connected input windings of the fourth set of *n* transformers or a fourth set of *n* resonant networks connected in series with respective ones of the output windings of the fourth set of *n* transformers,
- a fourth set of *n* rectification circuits connected to respective ones of the output windings of the fourth set of n transformers and configured for supplying a fourth set of rectified transformer voltages to respective ones of the first set of *n* rectification nodes.

6. A dual active bridge DC-DC converter according to claim 5, wherein the first predetermined phase is 90 degrees, the second predetermined phase is 180 degrees and the third predetermined phase is 270 degrees.

7. A dual active bridge DC-DC converter according to any of the preceding claims, wherein the first input driver comprises:
a first controllable semiconductor switch connected between the converter input and a driver output,
a second controllable semiconductor switch connected between the driver output and a negative DC supply rail; said driver output being connected to the series connected input windings of the first set of n transformers; and
first and second control terminals of the first and second controllable semiconductor switches, respectively, being connected to a modulated drive signal source.

8. A dual active bridge DC-DC converter according to claim 7, wherein each of the first and second controllable semiconductor switches comprises a MOSFET or an IGBT.

9. A dual active bridge DC-DC converter according to any of the preceding claims, wherein each rectification circuit of the first set of *n* rectification circuits comprises a plurality of controllable semiconductor switches.

10. A dual active bridge DC-DC converter according to any of the preceding claims, wherein each rectification circuit of the first set of *n* rectification circuits comprises a plurality of semiconductor diodes.

11. A dual active bridge DC-DC converter according to any of the preceding claims, wherein the *n* transformer windings of the current balancing transformer are wound around a shared leg structure of the common magnetically permeable core to conduct equal amounts of magnetic flux through each transformer winding.

12. A dual active bridge DC-DC converter according to any of the preceding claims, where the first set of *n* transformers comprises *n* individual transformers connected to *n* individual single-phase rectification circuits or *n* individual poly-phase rectification circuits; and
where *n* is even; each of the *n* transformer windings of the current balancing transformer has the same number of turns, N;
where *n* is odd; the current balancing transformer comprises *(n-1)* transformer windings with the same number of turns, N, and at least one transformer winding with (n-1)*N turns.

13. A method of adjusting load power supplied to a converter load by a dual active bridge DC-DC converter according to any of the preceding claims, comprising:
- applying a first pulse width modulated drive signal at a first phase angle to the series connected input windings of the first set of n transformers,
- applying a second pulse width modulated drive signal at a second phase angle to respective control terminals of a plurality of controllable semiconductor switches of each rectification circuit of the first set of *n* rectification circuits,
- adaptively adjusting a phase difference between the first phase angle and the second phase angle to reach a desired DC output voltage of the dual active bridge DC-DC converter.

14. A method of adjusting load power supplied to a converter load according to a claim 13, wherein a duty cycle of the first pulse width modulated drive signal is about

50 % and a duty cycle of the second pulse width modulated drive signal is about 50 %.

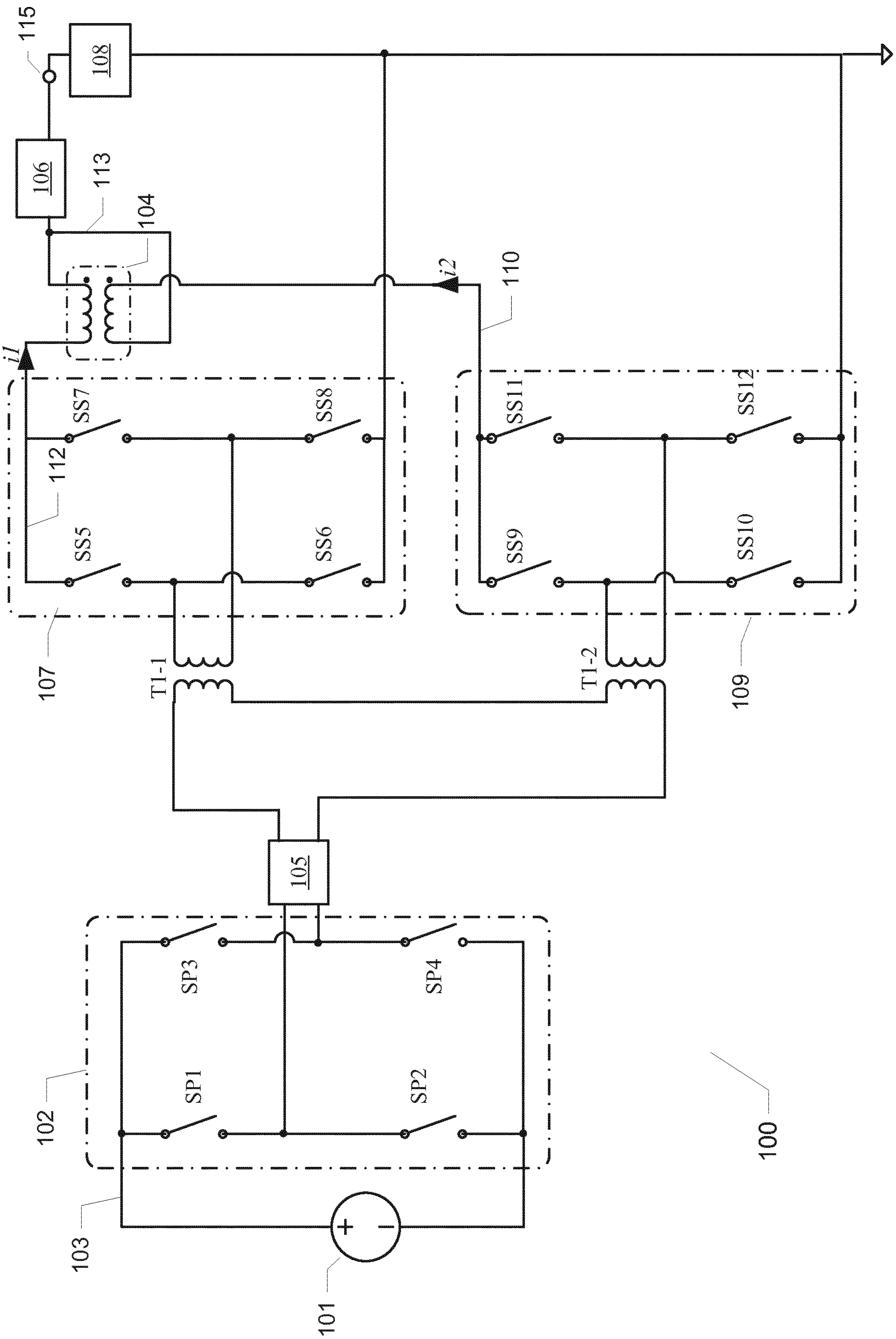

115
108
106
113
104
110
i2
i1
SS7
SS8
SS11
SS12
112
SS5
SS6
SS9
SS10
107
109
T1-1
T1-2
105
SP3
SP4
SP1
SP2
102
100
103
101

FIG. 1

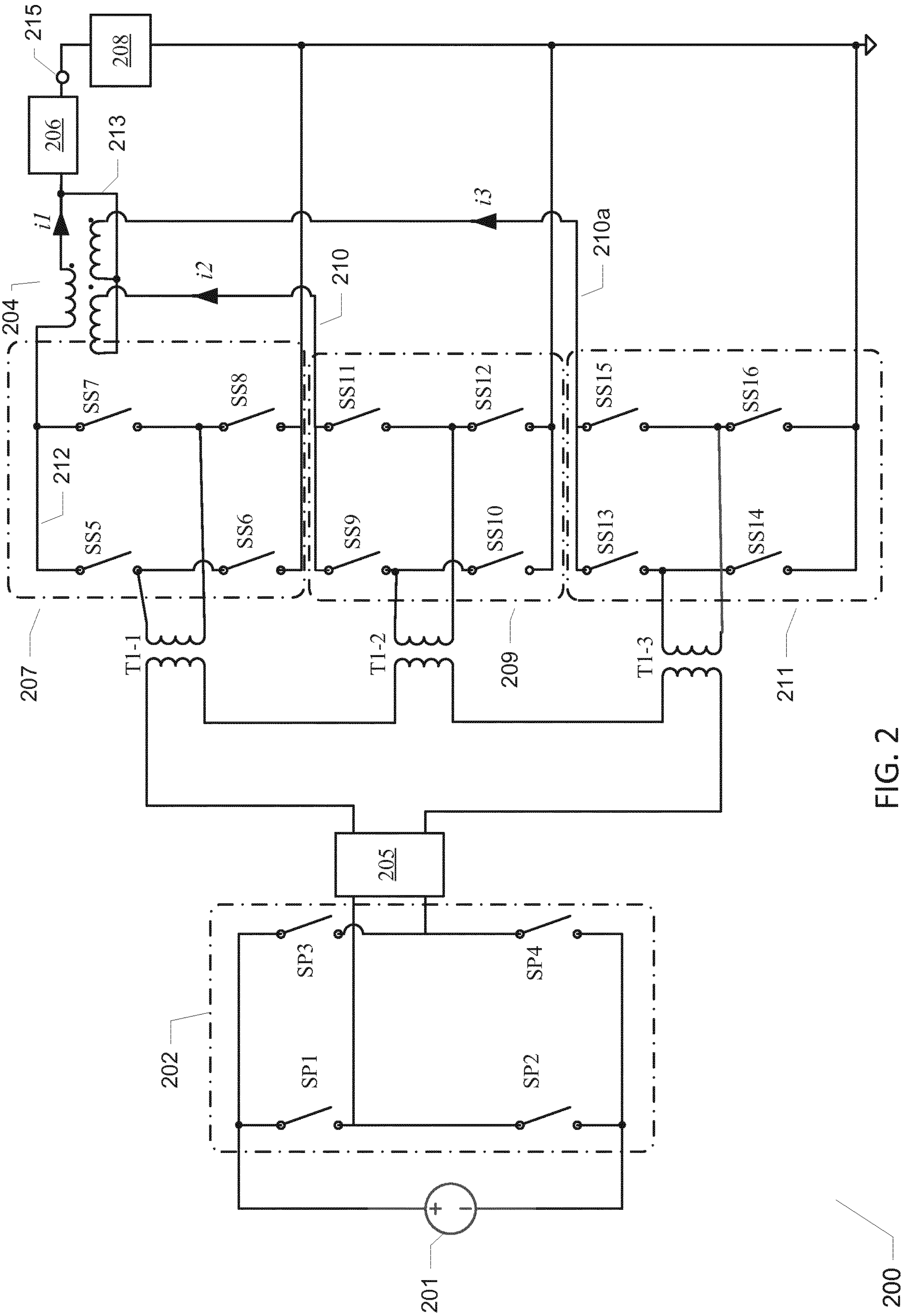

215
208
206
213
i1
i3
204
i2
210
210a
SS7
SS8
SS11
SS12
SS15
SS16
212
SS5
SS6
SS9
SS10
SS13
SS14
207
T1-1
T1-2
209
T1-3
211
205
SP3
SP4
202
SP1
SP2
201
200

FIG. 2

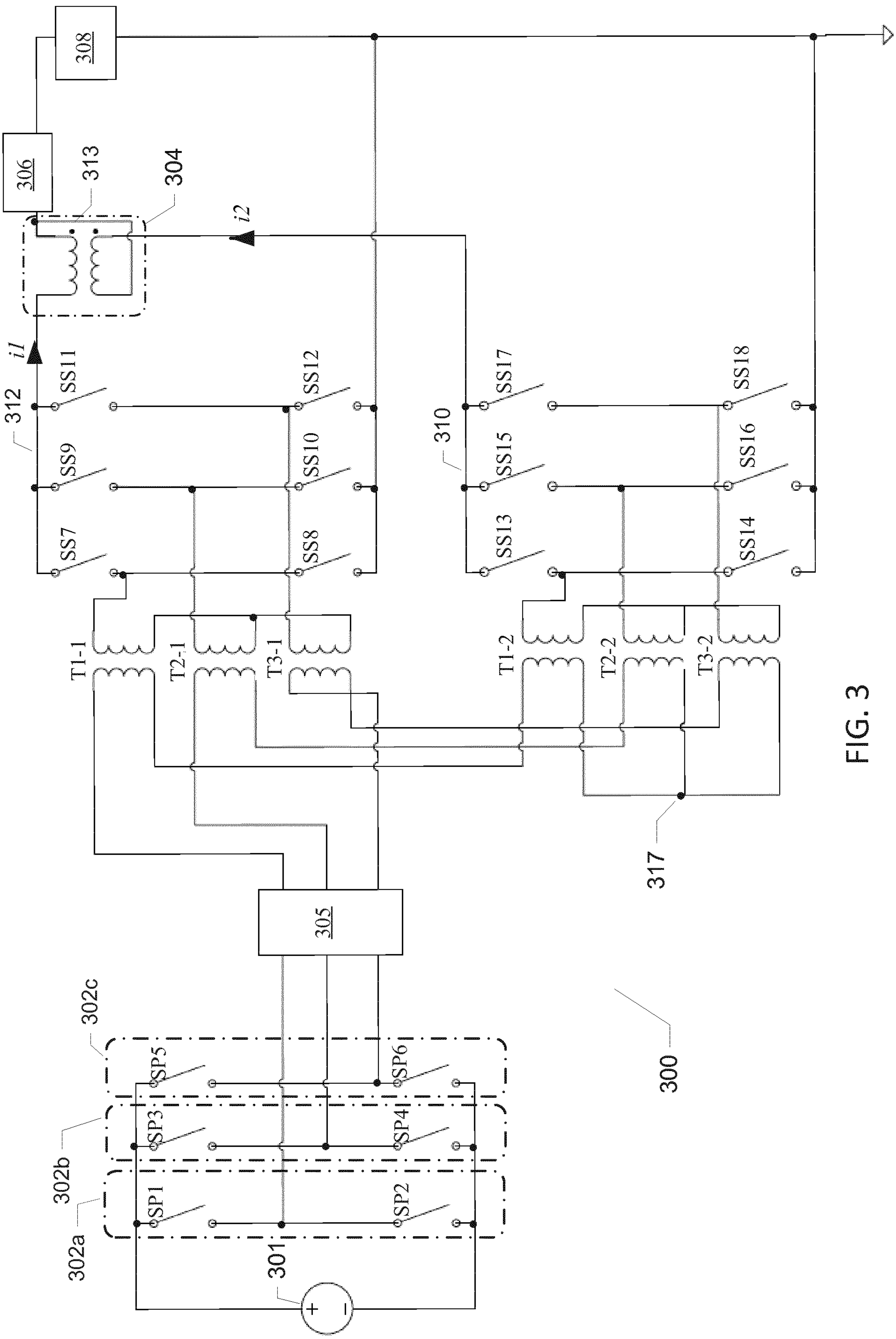

308
306
313
304
i2
i1
312
SS11
SS12
SS9
SS10
SS7
SS8
310
SS17
SS18
SS15
SS16
SS13
SS14
T1-1
T2-1
T3-1
T1-2
T2-2
T3-2
317
305
302c
SP5
SP6
302b
SP3
SP4
302a
SP1
SP2
301
300

FIG. 3

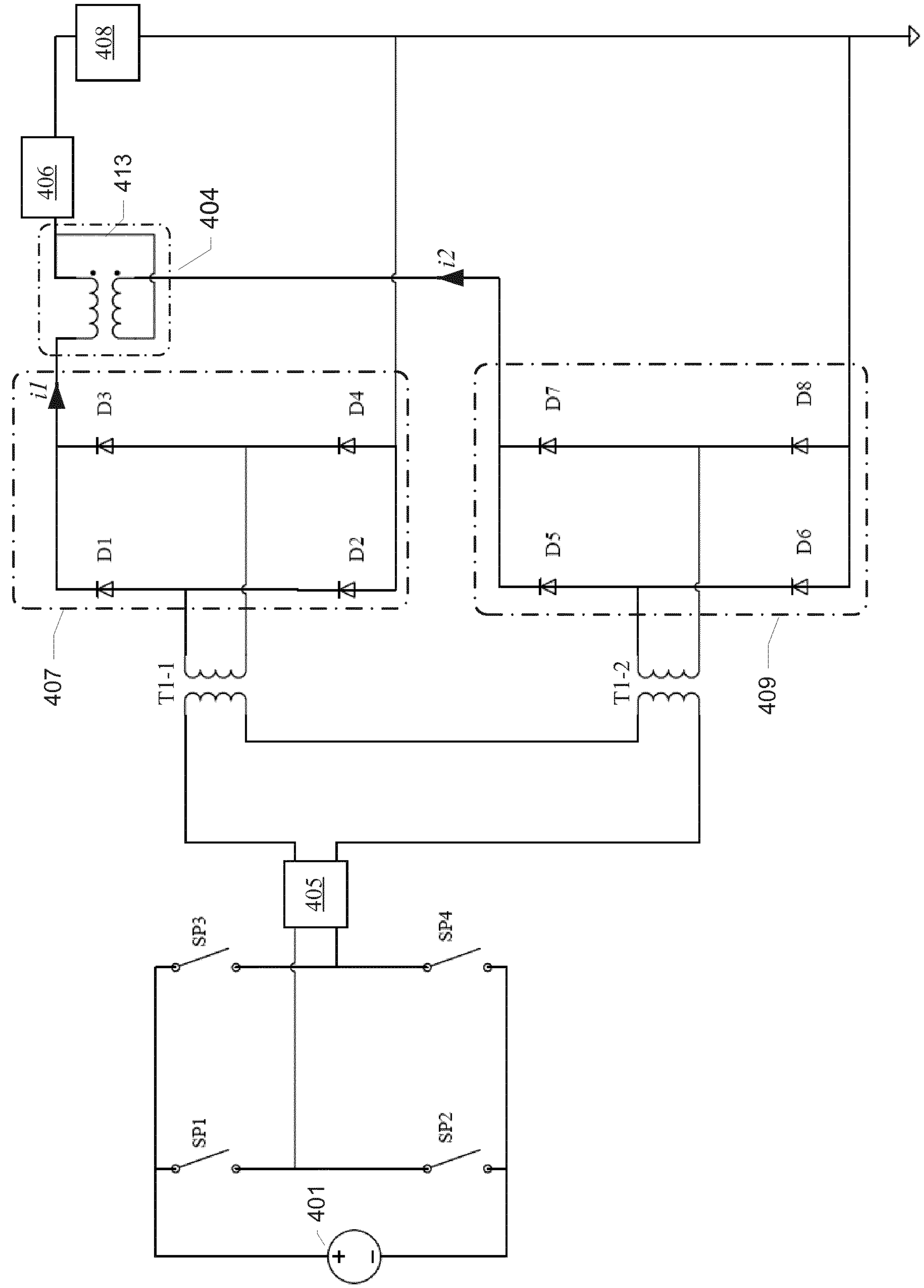

408
406
413
404
i2
i1
D3
D4
D1
D2
D7
D8
D5
D6
407
409
T1-1
T1-2
405
SP3
SP4
SP1
SP2
401

FIG. 4

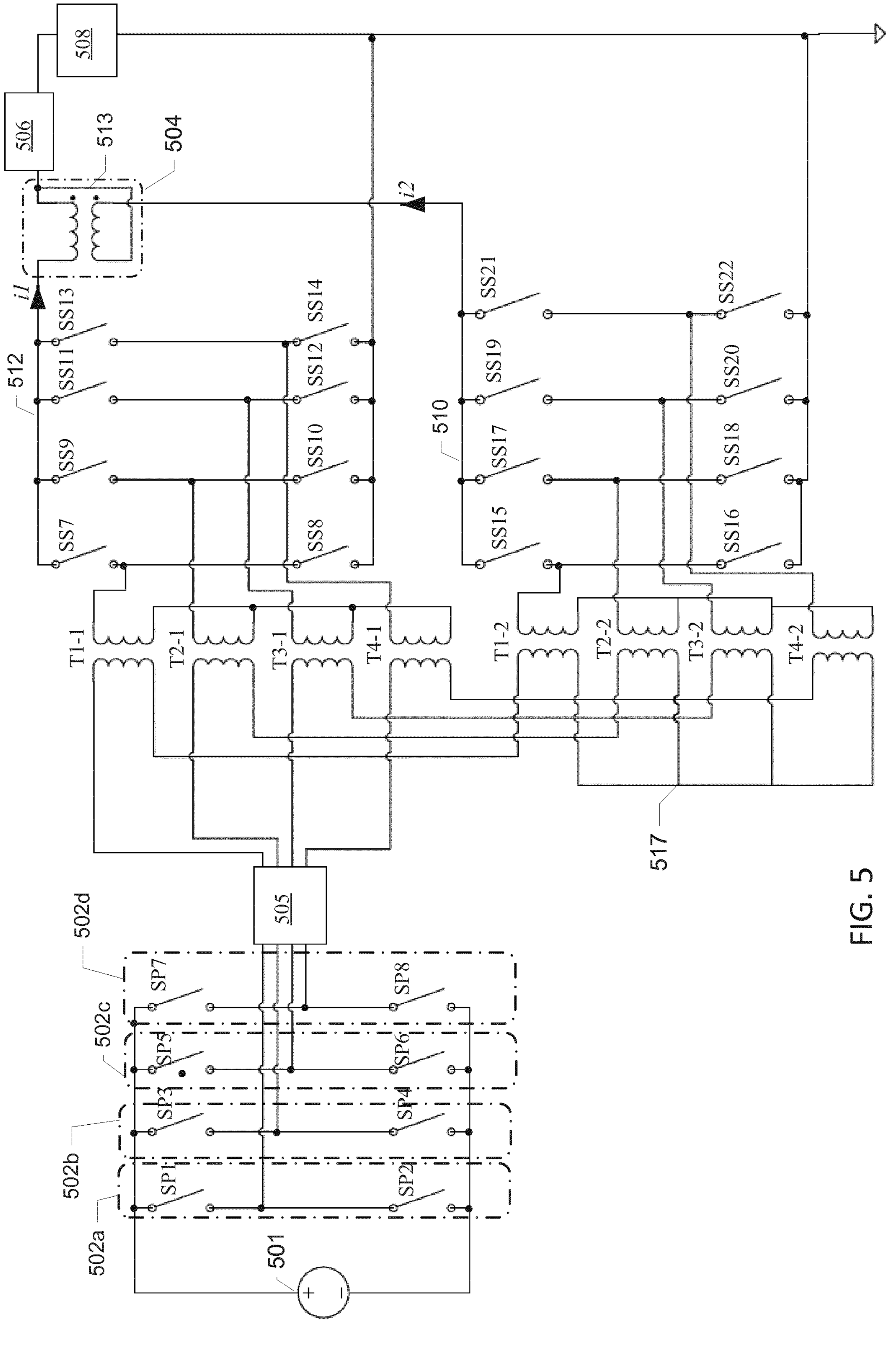

508
506
513
504
i2
i1
SS13
SS11
SS9
SS7
SS14
SS12
SS10
SS8
512
SS21
SS19
SS17
SS15
SS22
SS20
SS18
SS16
510
T1-1
T2-1
T3-1
T4-1
T1-2
T2-2
T3-2
T4-2
517
505
502d
502c
502b
502a
SP7
SP8
SP5
SP6
SP3
SP4
SP1
SP2
501
+
-

FIG. 5

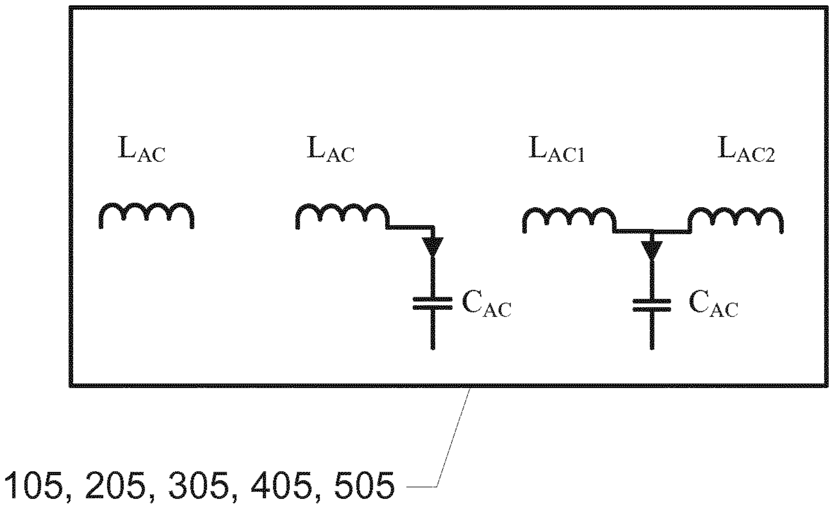
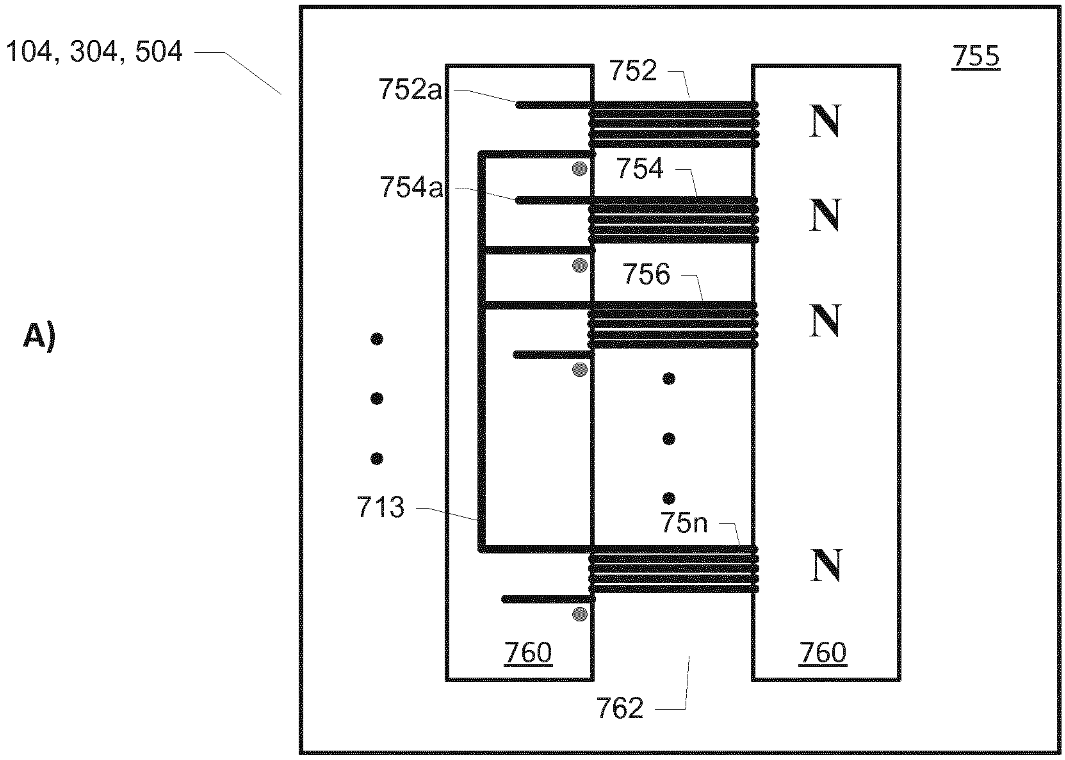


FIG. 6

A)


104, 304, 504
755
752
752a
N
754
754a
N
756
N
713
75n
N
760
760
762

B)

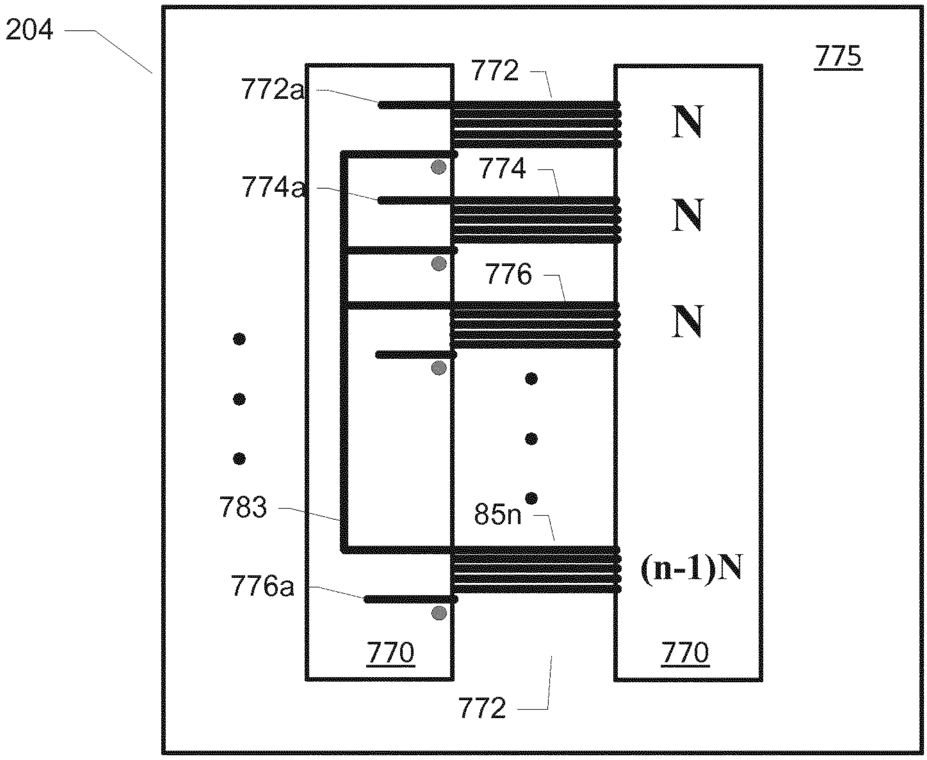

204
775
772
772a
N
774
774a
N
776
N
783
85n
(n-1)N
776a
770
770
772

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/079430

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M3/335 H02M3/28
ADD. H02M7/48

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02M H01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2 911 285 A1 (EATON CORP [US]) 26 August 2015 (2015-08-26) figures 5a, 7 paragraph [0005] paragraph [0013] - paragraph [0014] paragraph [0024] -----	1-14
X	JP 2005 033956 A (SONY CORP) 3 February 2005 (2005-02-03) abstract; figure 1 -----	1-14
X	US 7 239 530 B1 (DJEKIC OGNJEN [US] ET AL) 3 July 2007 (2007-07-03)	1,13
A	figure 1 -----	2-12,14
A	CN 2 718 892 Y (ZHONGHENG ELECTRIC CO LTD HANG [CN]) 17 August 2005 (2005-08-17) figure 1 -----	1-14

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2018	26/01/2018

Name and mailing address of the ISA/	Authorized officer
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